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TEXAS-WEST GULF CYCLONES*

WALTER J. SAUCIER

[The University of Chicago, Chicago, Ill.]

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ABSTRACT

From a study of 388 extratropical cyclones originating in the Texas-West Gulf region during a 40-year period various characteristics of their formation and early life history are determined. Some of the common synoptic sequences leading to the formation of these cyclones are derived from a more thorough study of recent synoptic charts and are described from the standpoint of the upper-air circulation. The 388 selected cyclones are summarized in terms of variations in frequency, favored regions of origin, motion, deepening, and relation to the rainfall of the central Gulf coast. The relatively great frequency of cyclone formation near the Texas coast is considered to result from the interaction of the general circulation on the unique physiographic environment of the region.

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INTRODUCTION

The weather and climate of the eastern United States during the cooler months of the year are influenced to a large extent by the frequency and behavior of extratropical cyclones originating near the northwestern coast of the Gulf of Mexico. These "Texas-West Gulf Cyclones," often referred to as "Texas Cyclones," appear under different conditions of low-level atmospheric circulation; also, similar synoptic situations may or may not produce cyclones. The cyclones exhibit not only variable frequencies of occurrence but also variable degrees of development. In some situations cyclones forming along the western Gulf Coast of the United States disappear or move away in the prevailing currents without further intensification; in others, they develop into storms of large magnitude, affecting most of the eastern states. In view of the idiosyncracies of these cyclones several interrelated types of formative sequences are described. Later, the statistical features of the cyclones are discussed.

For the purposes of this study the Texas-West Gulf cyclone was defined as the extratropical surface cyclone which, from evidence on daily sea level synoptic charts, formed within a designated area (fig. 11) and which persisted as a distinct cyclonic circulation for at least 24 hours. The area was bounded by the 89th and 105th meridians and the 25th and 34th parallels; the extreme southwestern corner in the Sierra Madre was excluded from the area. The general outline of the land area is similar to the one used in an earlier study of this nature by Bowie and Weightman [1], theirs being bounded on the north by the 35th parallel of latitude. This difference possibly accounts for some of the different results in climatic statistics.

SEQUENCES IN THE FORMATION OF THE CYCLONES

The important cyclone formations in the Texas-West Gulf region are associated with renewed upper level cyclonic activity near the 100th meridian in the form of

*Adapted from a master's thesis entitled *Climatic and Synoptic Aspects of the Texas Cyclone*, The University of Chicago, August 1947, of which part was reviewed at the Chicago meeting of the American Meteorological Society, December 29-30, 1947.

either a closed circulation or an extended trough through central North America at some time following a cold air outbreak over the central states. Just as the cyclones follow variable modes of development after their detection at the surface, there are different degrees of attendant flow pattern. A suitable description of this cyclogenesis required a break-down or division of the cyclones into a convenient number of categories depicting the usual formative stages. Groups were formed by determining the common sequences of changes preceding cyclogenesis and the common patterns both preceding and attending the new formations at the surface. Admittedly, no rigorous classifications were made; the ones adopted serve only to describe some dominant yet simple features in this cyclogenesis without attempting to explain the dynamics of cyclogenesis.

The formulation of cyclone groups resulted from a detailed analysis at two or more levels of the atmosphere of all cases occurring between October 1932 and December 1938 and from 1943 to 1947, and from brief surface synoptic summaries written for each cyclone case from 1899 to 1938. The charts used for this purpose included the *Historical Weather Maps, Daily Synoptic Series, Northern Hemisphere Sea Level, 1899 to 1939; Historical Weather Maps, Daily Synoptic Series, Northern Hemisphere, 3,000 Dynamic Meters, 1932–38;* twice-daily sea level and 10,000-foot (or 700-mb.) Northern Hemisphere charts, 1943–46, prepared by the Extended Forecast Section of the U. S. Weather Bureau; and daily 1,000-mb. and upper-level Northern Hemisphere charts, 1946–47, prepared at the University of Chicago.

A first condition common to all of these cyclones is the presence of polar or arctic air at the surface over the United States. Only one minor group of cyclones occurs when surface tropical air is present west of the Appalachians. Otherwise, polar air covers the entire country north of the latitude of the impending cyclone. This polar air can possess almost any degree of modification; empirically, the fresher the polar air the more the cyclone development resembles that of the polar front wave model. Although the polar front *at the surface* usually becomes increasingly indistinct while moving southward over the Gulf of Mexico and neighboring regions, the solenoid field associated with the front in levels above the surface is maintained for a considerably longer period of time. Low level convergence and a usual deformed field of motion in a developing cyclone, placed on the temperature field near the Gulf Coast, can aid in the reactivation of the polar front even at times when the front has apparently lost most of its significance. It is evident that the polar front, an accepted mechanism in the general circulation, does partake in this coastal cyclogenesis.

The cyclones studied were separated into two main divisions based on the source of their formation. These were further subdivided according to special features of formation.

A. CYCLONES FORMING FROM THE SOUTHWEST COLD-CORE LOW

The most determinate type of formation, yet possessing masked sequences at the surface, is manifest through the eastward motion of an upper cyclonic center from the extreme southwestern United States or the vicinity of Lower California. These cold-core cyclones are frequently isolated for periods of days near the coast of southern California and very often have indifferent pressure distributions at the surface. The eastward movement of such a center across the Rockies provides for a reliable type of surface cyclogenesis near the northwestern coast of the Gulf of Mexico if the pre-existing conditions there are favorable. Those centers having significant sea level low pressure areas which can be traced across the mountains generally show surface intensification as they reach the Gulf region, but for the purposes of this study such transient cyclones were not included. Over the Texas region several variations of development arise, depending on the circulation pattern and on the low-level air-mass structure east of the Rockies. All cyclones which resulted from the Southwest Low were placed in either of two groups which have distinguishing features.

Group 1. Low Latitude of the Westerlies East of the Rockies.—The first group of cyclones is most frequent during the winter months. This type of cyclone forms along a usually well-marked and persistent quasi-stationary front oriented along the northern Gulf Coast; this condition is attended by a low latitude position of the westerlies to the east of the Rockies. The synoptic pattern before cyclogenesis includes a broad cold anticyclone or north-south ridge at the surface dominating the United States east of the Rockies, upper cyclonic flow above this cold air, the polar front extending from the western Atlantic through the extreme southeastern United States, an indifferent or flat surface pressure distribution southwest of the Continental Divide, and a warm anticyclone situated north of its normal position in the extreme eastern Pacific with a ridge extending northward over the Canadian Rockies (figs. 1(a) and 1(b)).

The eastward motion of the upper cyclonic center is an essential mechanism in the formation of these cyclones. The displacement of this center is related to circulation changes in the Pacific, among them being a southward displacement of the Pacific anticyclone and of the upper westerlies lying north of this anticyclone; it is probable that there are also some common sequences in the Central Pacific. After the upper cyclone has become dislodged from its stationary position it moves eastward in the prevailing westerly current until it becomes an integral part of the circulation in the east. Evidence of pending cyclogenesis can be obtained from surface synoptic reports only after the upper center has begun to move toward the Gulf Coast. The precipitation with the resulting surface disturbance is usually widespread and steady. Since the surface air north of the front is coldest with this type of formation, these storms are the most conducive to sleet or glaze formation in winter

An example of this type of cyclogenesis is shown by figures 1(a) to 2(b). The sequence represents a very rapid formation along a clearly marked frontal surface. The conditions outlined above are prominent on the charts for the first day, February 19, 1947. Although the cut-off Southwest Low is very evident at 700 mb. and is even more pronounced in the higher troposphere, there is lack of its evidence from the sea level chart. During the succeeding 24 hours this center was traced

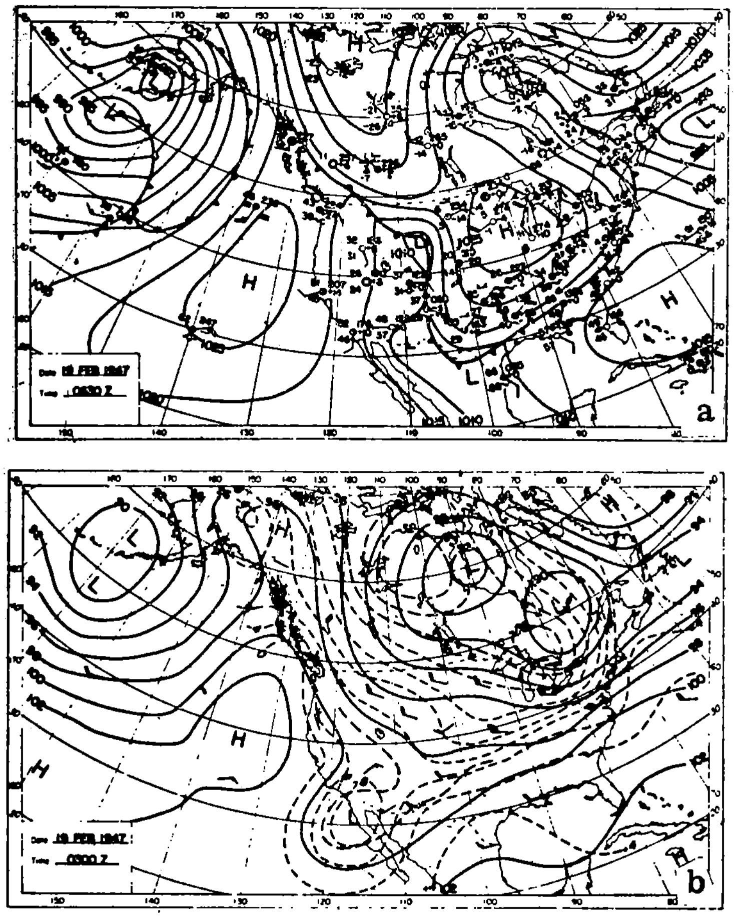

Figure 1.—(a) Sea level weather map, 0630 GMT, February 19, 1947. (b) 700-mb. chart, 0300 GMT, February 19, 1947. Solid lines are contours labelled in hundreds of feet; dashed lines are isotherms in °C.

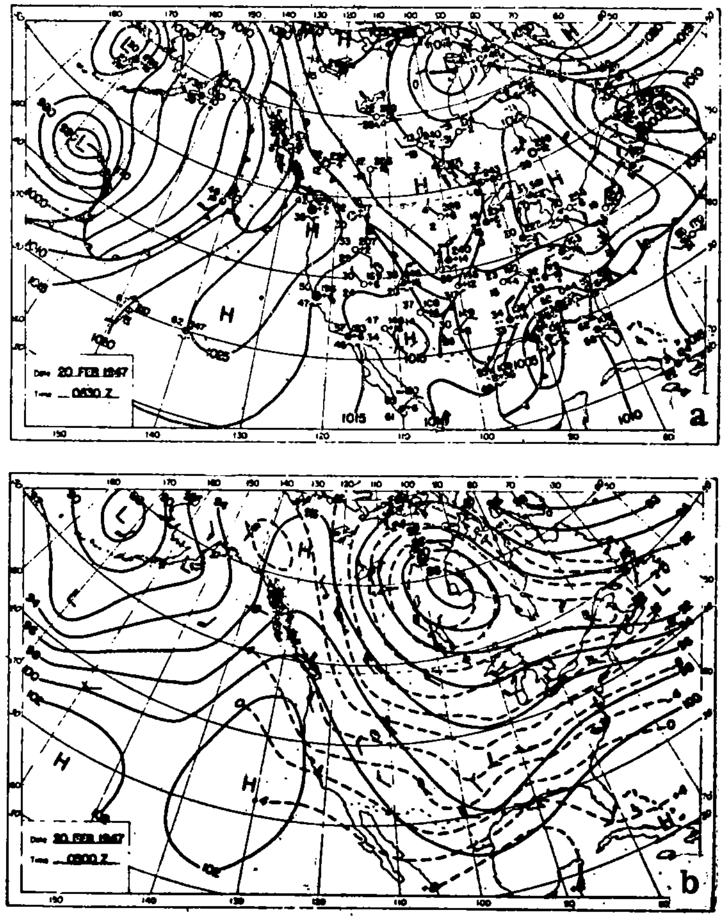

Figure 2.—(a) Sea level weather map, 0630 GMT, February 20, 1947. (b) 700-mb. chart, 0300 GMT, February 20, 1947. Solid lines are contours labelled in hundreds of feet; dashed lines are isotherms in °C.

in its rapid motion eastward. On the chart for February 20 it is shown over the vicinity of Arkansas. The new cyclone at the surface is now part of this same system. The eastward motion of this Southwest Low coincided with a southward shift of the Pacific anticyclone which in turn responded to pressure falls on its northwest side.

Group 2. High Latitude of the Westerlies East of the Rockies.—The other major subdivision of cyclones forming with the motion of a Southwest Low is most frequent during the autumn months. It is associated with fundamentally high-index [2] conditions over North America. The surface synoptic picture before surface cyclone formation is similar in some respects to the one in the first group, including the same general frontal orientation in the east. However, in this case the principal stream of westerlies has less amplitude at 700 mb. and is found at a higher latitude, near the Canadian border; the greater part of the cool air over the United States has come directly from the Pacific Ocean, the air east of the Rockies having been considerably modified in its trajectory, and a large portion of the cold air at higher levels having remained west of the Rocky Mountains to become associated with the Southwest Low. The polar front in the southern United States is weaker than in Group 1. At the surface the ridge line usually has a west-east alignment over the central United States with a flat anticyclonic center over the eastern States and another center over the Great Basin region or southwestern Canada. Beneath the main stream of upper westerlies there is often a secondary frontal or frontogenetic zone lying parallel to the upper flow near the northern border of the United States. This zone is usually referred to as the Arctic front.

During such periods of westerly flow frequent cyclonic perturbations are able to enter the northwestern States or British Columbia from the Pacific. The approach of one of these troughs in the westerlies with its attendant region of pressure falls produces a progressive southward increase of the west wind on the west coast. As in the previous case this appears to affect the stationary equilibrium of the Southwest Low, and it consequently moves eastward. East of the Rockies it may become associated with a Texas or Gulf Coast cyclone development and unstable forms of precipitation along the weak polar front. Figure 3 shows a Gulf Coast cyclone which formed from this sequence of changes. Several cyclones of this type occurred at regular intervals during the first half of January 1946, while the afore-mentioned pattern persisted for an unusually long period.

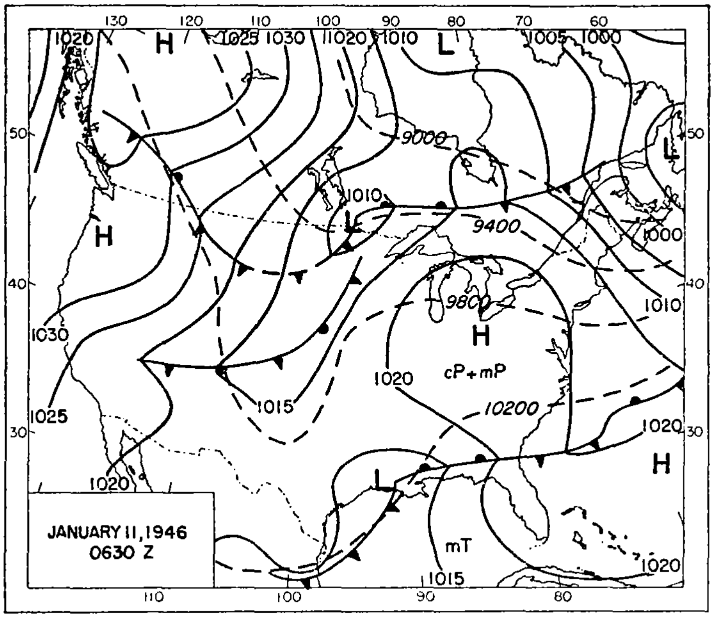

FIGURE 3.—An example of Group 2 cyclones showing sea level isobars (solid lines) and fronts, and 700-mb. contours (dashed lines) 0630 GMT, January 11, 1946.

An additional feature of this type of development is the presence of another surface cyclone almost on the same meridian but 20 to 25 degrees of latitude north of the Gulf Coast storm. After the Pacific trough enters the continent the cyclone remains in the stream of upper westerlies and is carried along the Arctic front which extends eastward from the Rockies. This dual cyclone structure over the United States is not restricted to this group alone.

B. CYCLONES FORMING FROM THE GREAT PLAINS TROUGH

The second major division of cyclones is attended by the redevelopment, or retardation of an upper trough of large amplitude just east of the Rockies. The first two groups (Groups 3 and 4) of cyclones in this division are associated with the retrogression or discontinuous redevelopment of the upper trough immediately following a cold air domination of the eastern half of the United States. The surface pressure distribution over the United States is consistently composed of two separate anticyclonic cells, one west of the Continental Divide and the other associated with the cold air to the east. During the two days preceding cyclogenesis there are persistent pressure falls at most levels near the 100th meridian, and net pressure rises near the Atlantic and Pacific coasts. The eastern anticyclone extends to higher and higher levels and moves northeastward; it is usually centered over the northeastern states when the new cyclone develops.

In contrast to the cyclones in Groups 3 and 4, those in the final group (Group 5) in this division form with the primary outbreak of cold air and in conjunction with the marked deceleration and persistence over the Plains of a previously eastward-moving upper trough.

Group 3. Retrogressive Upper Trough.—Group 3 comprises the largest single group of cyclones and basically it represents most clearly the principle of the processes leading to cyclogenesis in the Texas-West Gulf region. Cyclones with related surface sequences for which individual examples could not be considered representative of a large number were also placed in this group during the classification of the cyclones. A frequent sequence involved in these extra cases was the slow eastward motion of a large trough or closed cyclone at upper levels over the Colorado region. These usually gave rise to large surface cyclones north of the Texas-West Gulf region, and the Texas cyclones were small subsidiary centers which usually lost their identity during the course of the next two days. However, the general surface pressure pattern is similar to the typical cases of this group, and the induced pressure falls over Texas leading to the new cyclones are part of the sequences of this group. Although Group 3 becomes less definite than the others because of these miscellaneous cyclones, statistics on the cyclones occurring after October 1932 show that the features to be described below are representative of no less than four-fifths of the cyclones in the group.

The description of this group is conveniently introduced by referring to the typical case of December 19–20, 1946 (figs. 4 (a) to 5 (b)). This particular situation was preceded by cold air movement southeastward over the United States. On December 18 the principal front at the surface extended from Nova Scotia to the central Gulf Coast, the cold anticyclone was centered over Oklahoma, and the 700-mb. flow consisted of almost constant cyclonic curvature over the United States with the southern limit of the pressure contours located about on the 90th meridian. The pattern was otherwise essentially the same as on the 19th. In the intervening 24 hours there was apparent splitting of the 700-mb. trough, a zone of maximum cyclonic curvature forming on either side of the trough position of the previous day and pressure rises occurring between these two troughs. At the surface the front progressed slowly southeastward while appearing to weaken in the vicinity of the Gulf of Mexico. The cold anticyclone moved northeastward while intensifying. Pressure falls continued east of the Rockies with a large isallobaric center located in west central Canada. By the 20th the Great Plains trough at 700 mb. had become sharper and moved slowly eastward toward the Gulf; it had now become the major trough over North America. On the surface chart a new frontal wave with weather appeared on the Gulf Coast, where the front was previously undergoing dissolution. Its formation there along the reactivated polar front followed large scale atmospheric changes which took place in a period of several days.

The fact that during this sequence the flow pattern over the west coast of North America and the extreme eastern Pacific remained almost constant on the successive days precludes an explanation of the new major trough by its motion from the Pacific. There was trough intensification to the rear of the previous trough such that the net 48-hour change was equivalent to retrogression by 10 degrees of longitude at 700 mb. This change appears to have been part of a large readjustment process in the hemispheric circulation which is suggested in figure 6 by the successive daily positions at 700 mb. of the 10,000-ft. contour which was located along the southern edge of the

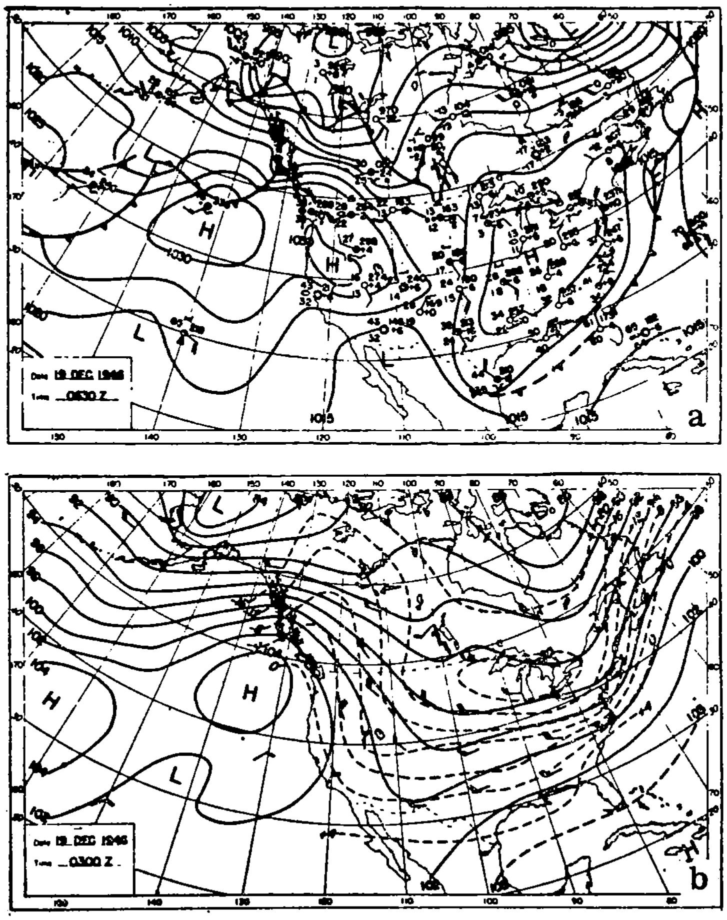

Figure 4.—(a) Sea level weather map, 0630 GMT, December 19, 1946. (b) 700-mb. chart, 0300 GMT, December 19, 1946. Solid lines are contours labelled in hundreds of feet; dashed lines are isotherms in °C.

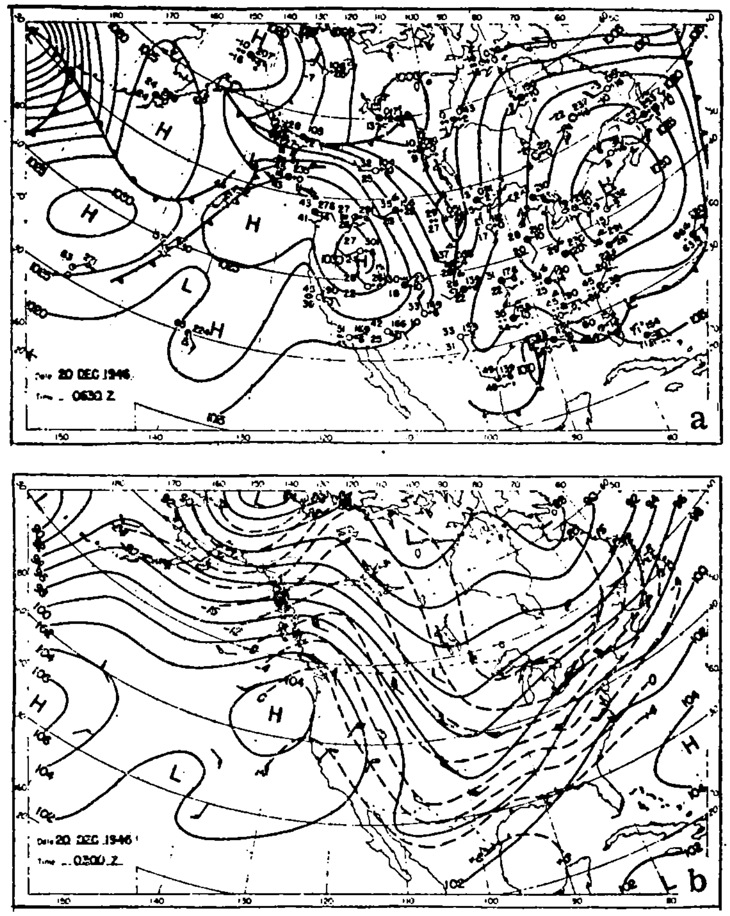

Figure 5.—(a) Sea level weather map, 0630 GMT, December 20, 1946, showing a deepening wave cyclone on the Gulf Coast and the co-existence of cyclonic circulations on the northern and southern borders of the United States at almost the same longitude. (b) 700-mb. chart, 0300 GMT, December 20, 1946. Solid lines are contours labelled in hundreds of feet; dashed lines are isotherms in °C.

main westerly current and which passed through the southern United States. Troughs B and C showed the usual eastward motion during the four days. The cyclonic intensification to the rear of both B and C led to acceleration and filling of these two troughs. Intensification in the rear of the Pacific trough was followed in about two days by a similar process over North America while the West Coast ridge underwent only minor changes. This readjustment is in accord with the description of the interdependence of large-scale systems in the circumpolar westerlies [3] and with Rossby's [4] discussion of downstream propagation of energy in atmospheric waves. Although the more common type of retrogression observed was of the form in which a trough of very small amplitude in the northwesterly current was subjected to intensification, the essential features are the same.

The importance of this retrogression in the formation of surface cyclones in the Texas-West Gulf region is revealed by the fact that 22 of the 25 cyclones of this group which occurred between 1932 and 1938 resulted from this same process. In each case there was either a similar retrogression or an intensification of the southerly current in the central Pacific prior to or simultaneous with the retrogression in North America.

Group 4. Discontinuous Redevelopment of the Upper Trough.—The next group of cyclones associated with the development of a Great Plains trough at upper levels possesses a less common and more restrictive type of formation, but occurs with even more abrupt changes in the flow pattern over the United States. These cyclones are associated with somewhat later stages of the cold spell in the east. Following a cold outbreak similar to the one of December 18–19, 1946 (fig. 4(a)), the main current of westerlies may shift northward over the United States with relaxation of meridional flow. Such a change ordinarily presages fair and mild weather for most of the States. The general warming coincident with this shift does not necessarily involve movement of tropical air

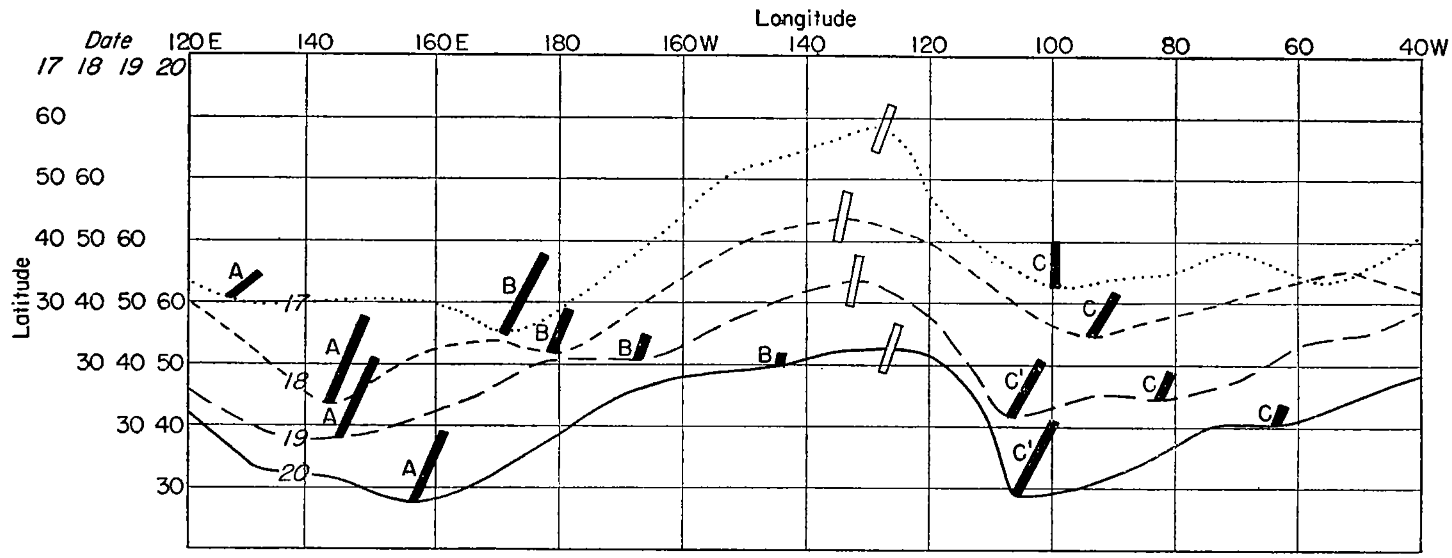

FIGURE 6.—Successive daily positions of the 10,000-ft. contour at 700 mb. December 17–20, 1946. The slope and length of the solid shafts represent the orientation and relative intensity of the troughs respectively. (All data taken from charts prepared by Extended Forecast Section, U. S. Weather Bureau.)

over the United States; rather, the Gulf front appears gradually to weaken or dissolve at the surface while there is a lag in the dissipation of the temperature gradient attending the front in higher levels, and warming occurs in the polar air itself. The front at the surface is usually dropped from surface analyses some time before the new cyclone formation. As the amplitude of the upper flow decreases, the northern section of the west North American high pressure ridge becomes of less influence, and disturbances from the Pacific begin to penetrate the continent at the latitude of the stronger westerlies.

One of the first of these minor troughs which cross the mountains appears to be a nucleus of trough intensification leading to the Texas cyclone. Usually following marked cyclonic intensification in the Pacific between longitudes 180° and 140° W., pressure rises occur in the western and eastern States, and there are pressure falls of initially smaller magnitude over the Plains. This phase of the process has been discussed by Cressman [5] in using the situation which led to the cyclogenesis in western Texas shown in figure 7. The surface pressure falls are concentrated in two centers, the major and sustained one over Texas, the minor and temporary one with the surface cyclone in the Dakota-Montana region. Surface and upper cold air begin moving rapidly southward east of the mountains while a sharp and extended upper trough is formed there. The Dakota cyclone decelerates and is subjected to slow filling. As the cold air continues to move southward, the surface cold front which separates the two polar air masses assumes a north-south alignment in the Mississippi Valley. The Texas cyclone develops along this front (fig. 7), although there are many cases in which the cyclone first appeared east of this front. With the strengthening of the cyclonic circulation surface tropical air is brought into the new cyclone which then acquires some characteristics of the usual frontal wave.

The sequence described above usually takes place in two to three days. It is also necessary for this rapid

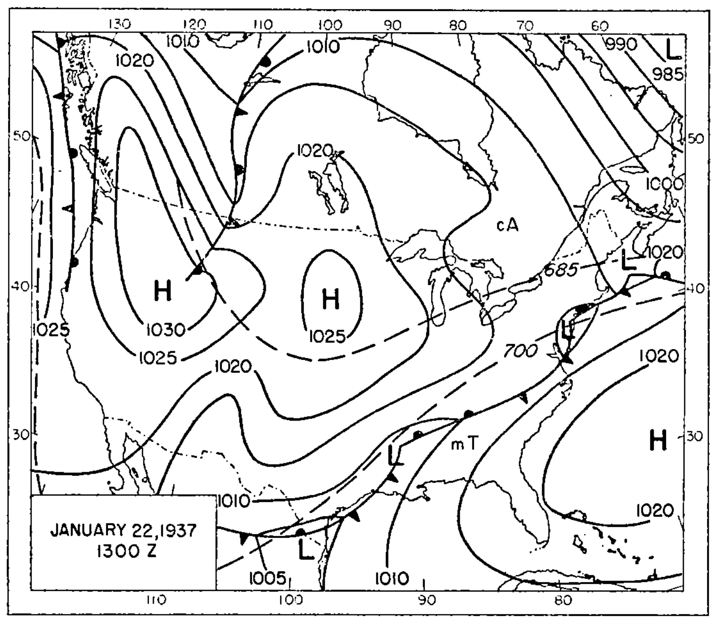

FIGURE 7.—An example of Group 4 cyclones showing sea level isobars (solid lines) and fronts, and 700-mb. contours (dashed lines), 0630 GMT, March 12, 1947.

cyclogenesis that the major portion of the southward moving cold air be located east of the Rocky Mountain range; otherwise, the cold air could stagnate west of the mountains for some time and different situations would result. Therefore, the location of the major wave pattern in the eastern Pacific is an important condition for the location of the deepening Great Plains trough and the resultant Texas cyclone.

The precipitation in the early stages of this Texas cyclone is often concentrated in the eastern or southeastern quadrant of the surface cyclonic circulation at a considerable distance in advance of surface fronts. It can be of a very unstable nature, particularly if there is rapid intensification of the cyclone. This storm is very conducive to the formation of tornadoes near the Gulf Coast.

Group 5. Persistent Upper Trough.—While the two previous groups account for the cyclones forming in conjunction with discontinuous retrogression of cold troughs over North America and polar air at the surface on both sides of the upper trough, this last group contains the cyclones forming with the primary outbreak. When a large cold trough decelerates sharply or stops over the Plains after normally moving eastward, a situation is set up for the maintenance of a pronounced quasi-stationary front beneath the strong upper southwesterly current. This front, separating very cold continental air from the real tropical air in the southeast, assumes an orientation southwestward to the Texas region (fig. 8), and along the front small waves can emanate at frequent intervals. A suitable description of the pattern involved can be imagined by shifting the mean upper flow pattern of North America and adjacent parts of the oceans approximately 30 degrees of longitude westward. Thus, the Atlantic anticyclone extends into the southeastern states, the mean East Coast trough is found in the central part of the continent, and the western ridge extends northward into the Gulf of Alaska. Although such a pattern is abnormal, it occassionally persists for several days with only slight changes in position. Examples of this sustained situation with numerous frontal waves originating along the sharp front are depicted by charts for much of January 1937. The Ohio Valley floods of that period have been attributed to such an abnormal and persistent pattern [6].

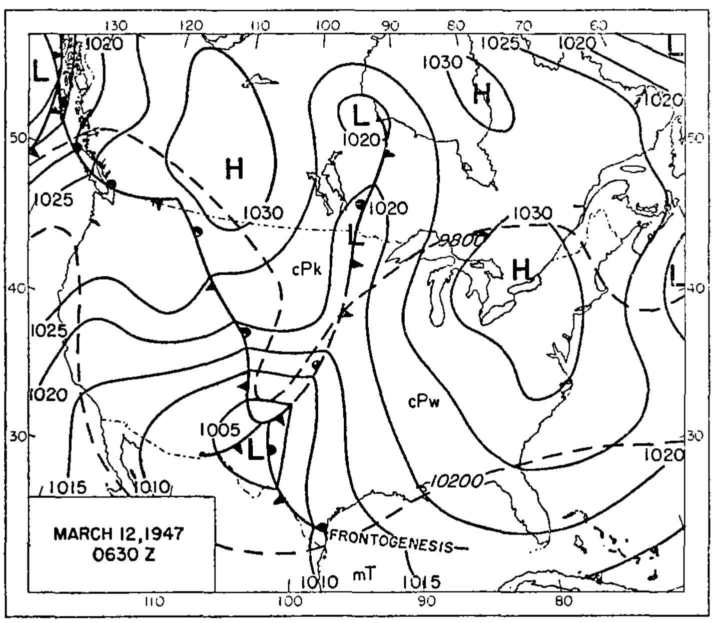

FIGURE 8.—An example of Group 5 cyclones showing sea level isobars (solid lines) and fronts, and 3-km. isobars (dashed lines), 1300 GMT, January 22, 1937.

The Texas-West Gulf cyclones forming under these circumstances are very similar to the more frequent waves described by Miller [7] which form on active fronts extending parallel to the Atlantic coast. This group is the only one in which the cyclone waves are observed to occur in families. These waves seldom reach occlusion before arriving over the northeastern states or the Atlantic. The precipitation is mostly in a relatively narrow band along the path of each wave. The centers move so rapidly along the front and the waves have such small amplitude in their early stages that it is difficult to trace the development of an individual wave on daily charts. This difficulty is believed to have minimized the number of such cyclones which conceivably could have been included in the original selections. There is also a tendency for these small waves to originate along various sections of the front without preference for the Texas-West Gulf region, but the fact that they occur in the region is sufficient reason for including them in the study.

CLIMATIC FEATURES OF THE CYCLONES

The ensuing statistical data are based on the 388 cyclones selected in the manner described in the Introduction from the months October to April of the 40-year period 1899 to 1938. The basic source material consisted of the *Historical Weather Maps, Daily Synoptic Series, Northern Hemisphere Sea Level, 1899 to 1939*, published by the U. S. Weather Bureau, from which all cyclones were selected as a result of a day-to-day examination of the synoptic charts. The cyclone track summaries of the *Monthly Weather Review* provided a means for cross-checking with the daily charts. The number of selected cyclones for the 40 years is closely proportional to the number found by Bowie and Weightman for the same months; the difference amounts to two percent.

DISTRIBUTION OF CYCLONES BY MONTHS

The distribution of cyclone frequencies for each month of the 7-month season during the entire 40 years is represented by an almost symmetrical curve centered on January (fig. 9). The curve assumes even greater symmetry for the season when the frequencies are corrected to months of equal length (approximately 30.3 days). Some distortion of curvature is produced by a rather rapid increase in frequency from November to December and a more gradual decline in late winter and early spring; this distortion approaches that of the rainfall distribution of the Lower Mississippi Valley and the southern Appalachian region for the same months.

There is considerable aperiodic variation in the month of maximum cyclone frequency, and only few seasons are characterized by distributions parallel to the 40-year total in figure 9. The difference between the distribution found by Bowie and Weightman and the one for the 40 years cannot be readily explained. A computation for the overlapping period, 1899 to 1912, confirms their curve by also producing a December maximum. During the remaining years a January maximum was most common; February and March occasionally had the maximum for the season.

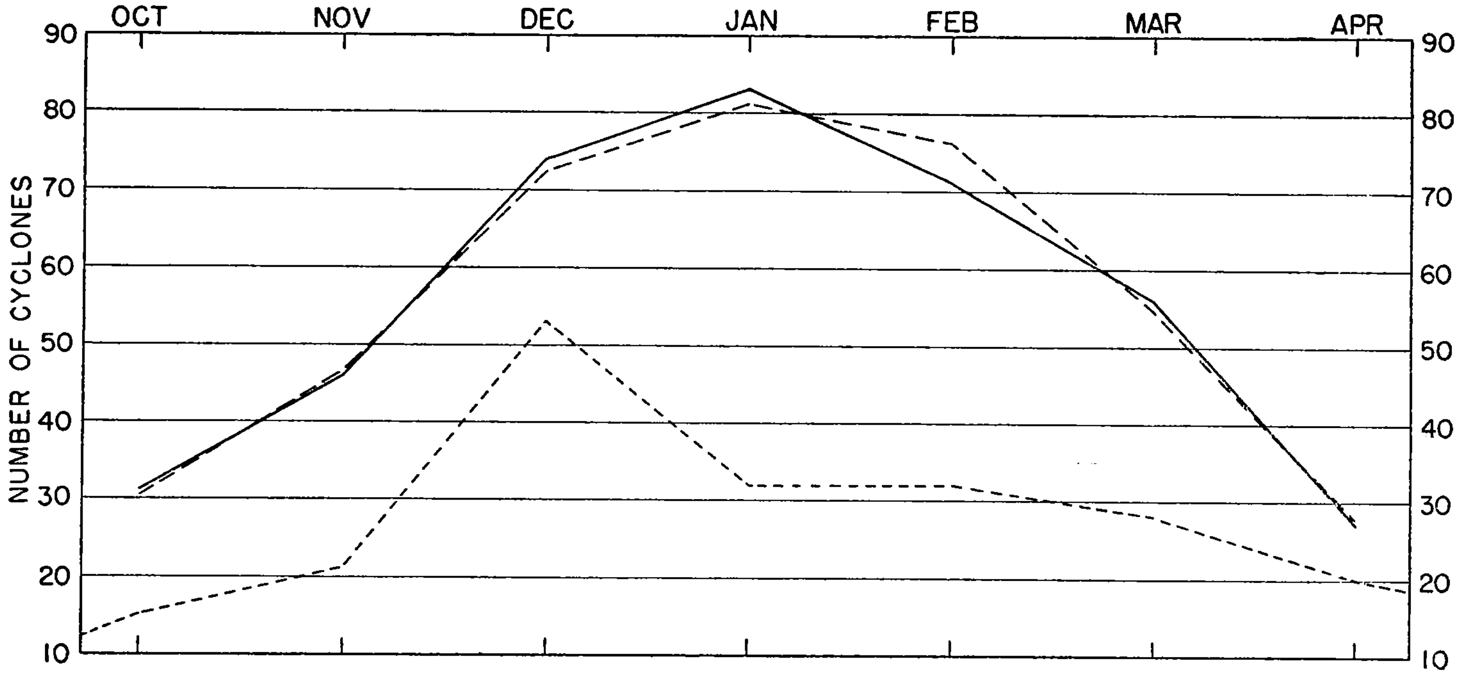

FIGURE 9.—Monthly distribution of frequencies of Texas-West Gulf cyclones. Actual frequency 1899–1939, solid line; frequency corrected to months of equal length, long dashes; distribution by Bowie and Weightman [1] for 1892–1912, short dashes.

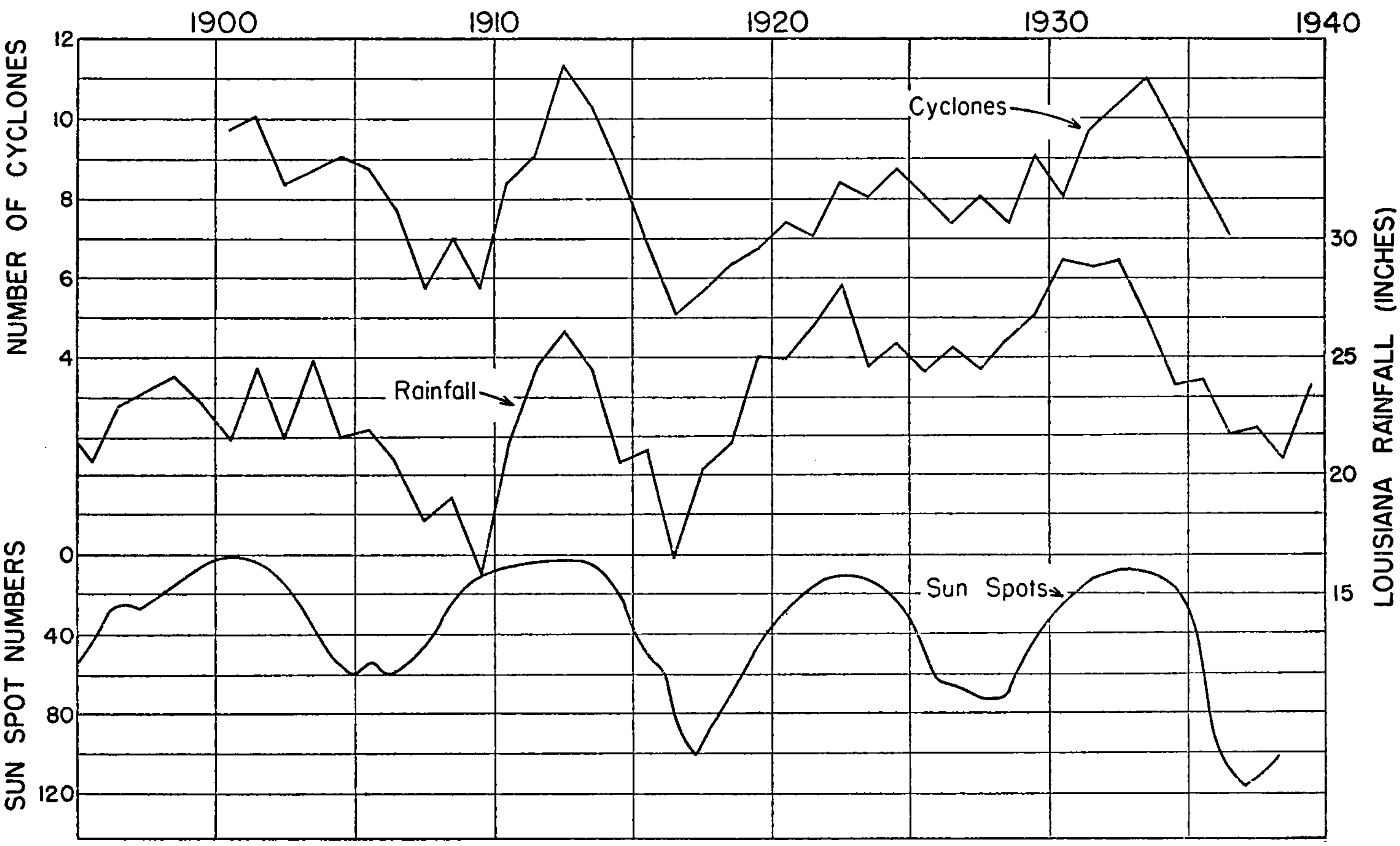

FIGURE 10.—Periodic variation in cyclone frequency compared with the variations of average Louisiana precipitation and of sunspot numbers.

INTERANNUAL VARIATION OF CYCLONE FREQUENCY

The average annual number of cyclones was slightly less than 10. The greatest annual number occurred in 1899 with 19 cases and the minimum in 1916, a relatively dry year, with only 2. The interannual variability was 3 cyclones, or about one-third of the average annual number.

For the analysis of the statistical material presented in the next few sections the seasonal period (October through April) instead of the annual period is considered. In the remainder of this section October and April are excluded.

The statistics on seasonal cyclone frequency indicate that periods of maximum and minimum activity tended to repeat themselves in a regular fashion. Part of this variation could be accounted for by inaccuracies in the selection of cyclones and to a lesser extent perhaps in the actual map analysis. However, such inaccuracies could just as well serve conversely to smooth out natural variations. A curve of the three-season-average cyclone frequency is shown in figure 10. The curve reveals regions of maxima and minima having periods of approximately 11 years. The climatic importance of this variation is evident from the great amplitude which is shown even after averaging. An inspection of the similarly smoothed curve of Louisiana rainfall for the same months as obtained from summary data in *Climatological Data for the United States by Sections* corroborates this cyclone variation. Periods of more frequent cyclogenetic activity near the Texas coast should *a priori* also be periods with larger amounts of precipitation over a flat area immediately to the northeast. The precipitation scale represents a variation from near-drought to flood conditions. The similarity of the two curves even in the unusual decade after 1920 is outstanding, although the linear correlation between cyclone number and inches of rainfall is rather small. A more detailed description of the relation of cyclones to rainfall follows in a later section.

A comparison of these variations with the more widely known variation of solar activity is afforded in figure 10 by the inverted form of Clayton's [8] sunspot curve. Again, the curves show variations of about equal length and good phase relations. Sunspots are generally considered to be correlated to solar radiation which in turn is a determining factor in the earth's atmospheric circulation.

LOCATION OF CYCLONE FORMATION

As a matter of convenience the site of first detection of each cyclone from daily charts was designated as the location of cyclogenesis. Since the cyclones normally move eastward, the exact point of origin would usually lie to the west of the assigned location.

The map presenting location of cyclone formation for the entire season October through April (fig. 11 (a)) shows a clustering of points which extends eastward from extreme southern Texas; this area coincides in location with the large surface temperature gradients for the season. An additional feature of the map is the scarcity of cyclones originating in western Texas; cyclones appearing over this region were usually observed to have moved in from the west near the Mexican border and could not all be included among those *forming* in the designated Texas-West Gulf area.

The clustering of points near the coast is even more

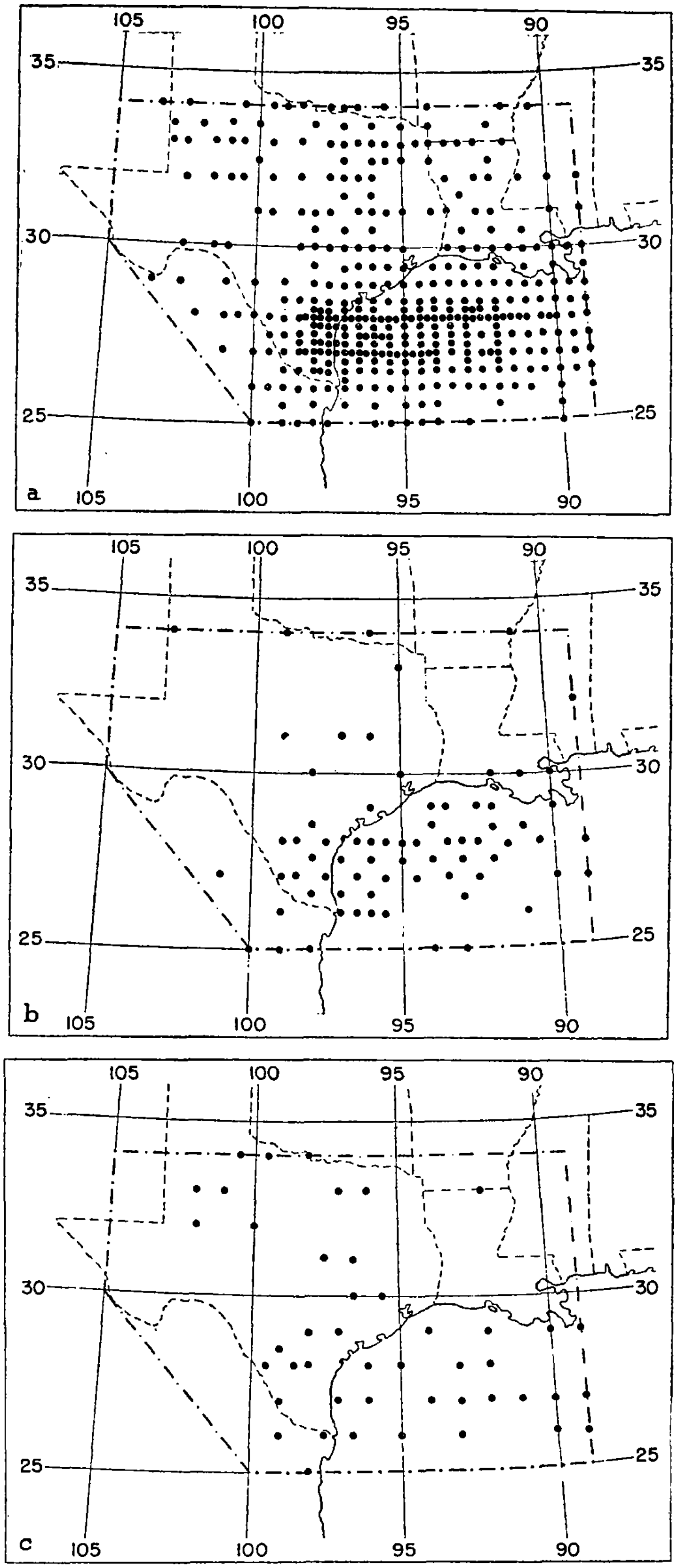

FIGURE 11.—Location of cyclone formation for (a) the seven months October through April, (b) February, and (c) November.

pronounced during the colder months. For example, during February (fig. 11 (b)) there is a concentration over the coastal waters off Texas and Louisiana, while during November (fig. 11 (c)) there is no definite grouping. Geographic distribution of cyclogenesis during October and April is very similar to that for November. It appears that if the coastal temperature gradient is effective in the processes of frontogenesis and cyclone formation, this temperature gradient is more influential during winter than in other seasons. But since there are many winter cyclones forming inland at some distance from the natural land-sea temperature contrast, and since cyclones are common in autumn and spring when this temperature contrast is relatively small, the frequency of cyclogenesis should not be attributed to this coastal temperature contrast only.

TRACKS AND SPEEDS OF CYCLONES

The movement of these low pressure centers was computed from their successive daily positions. The lower curve in figure 12 represents the frequency of motion along each ten degrees of compass direction from point of origin; the dashed curve gives the average speed along these paths. Two cyclones had net southwestward motion, and one remained stationary during the first day. The most frequent path taken by the cyclones was to the east-northeast, while the more rapidly moving storms moved slightly to the left of this most common track. Both frequency and speed drop off abruptly between 70 and 100 degrees from the origin.

During December, January, February, and March the distribution of cyclone tracks is characterized by a distinct modal direction toward 70 or 80 degrees; during the remaining months a minor mode appears at 30 to 40 degrees and the major one near 80 degrees. This suggests that the prevailing upper current over the surface center during formation and early history is usually west-southwest in winter and early spring. In the other months an

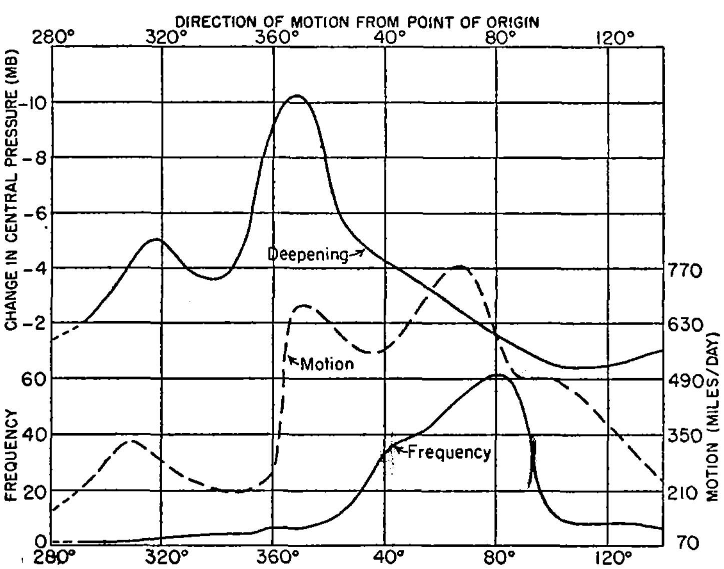

Figure 12.—Cyclone frequency, motion, and deepening for given direction of motion during the first day.

upper flow of larger amplitude, providing a northward component in the motion of the cyclone, is often necessary. The cyclones which moved with a westward component occurred principally during autumn and spring in association with subtropical synoptic conditions similar to those described by Riehl [9] in which a warm anticyclone intensified over the eastern States.

The cyclones move most slowly in October (table 1) when they average less than 400 miles per day. The average speed increases with the season, reaching more than 600 miles per day in January, and decreases very little from winter to spring. This lag in the distribution of average speeds is in agreement with the seasonal variation in the latitude of maximum zonal westerlies both at sea level and at 3 km. given by Willett [10]. During October, November, and April the smaller average displacement and the great tendency for movement toward northeast have the effect of minimizing the average displacement along the 30- and 40-degree tracks in figure 12; many rapidly moving storms follow these tracks in winter.

TABLE 1.—*Distribution of cyclone frequencies, motion, and deepening by months*

Month	Frequency	Average motion in first day (miles)	24-hr. change in central pressure (mb.)	
			First day	Second day
October	31	390	−2.2	−3.1
November	46	480	−3.4	−4.3
December	74	550	−3.6	−5.8
January	83	620	−1.9	−7.3
February	71	610	−2.3	−6.9
March	56	610	−3.9	−5.9
April	27	590	−2.3	−3.4
Total or average	388	570	−2.8	−5.8

DEEPENING OF CYCLONES

Statistics on the deepening of cyclones were obtained from daily estimates of the central sea level pressure of each cyclone. The final data are included in figure 12 and table 1.

Figure 12 shows that during the first day cyclones deepen most when moving northward, that is, when moving to the left of the most frequent and most rapid paths, and they show very little deepening when moving with a southward component. The cyclones moving along the principal track remain relatively weak during the first day. These are usually carried off with a strong upper current as stable frontal waves along the Gulf Coast and then deepen rapidly upon curving to the left over the Atlantic coastal region.

The seasonal trend in cyclone deepening undergoes an interesting cycle from October to April. An increase in deepening during autumn and a decrease during the spring months is to be expected. But there is a pronounced minimum in 1-day deepening during the coldest months (table 1), when the cyclones are most frequent and move most rapidly, when the westerlies are reaching their lowest latitude, and when the mean solenoid field along the coast is best developed. Again, average figures are very deceiving; many of the largest cyclonic developments take place during January and February. But there is also the tendency for small frontal waves to occur very frequently during these months. A computation of deepening during the second day was made for each month of the season to determine if the *rates* of cyclone deepening showed any variation. Although several of the selected cyclones lost their identity after 1 day, those cases were sufficiently well distributed over the season so as not to seriously affect the results given in the last columns of table 1. It is apparent from the data that during the colder months, cyclones deepen at a rapidly increasing rate, in the first 48 hours of their history. When the 2-day period is considered there is no significant minimum in deepening during January and February even though those cyclones usually have a delayed development.

Considering all characteristics of the cyclones which have thus far been summarized, it can be stated that the typical winter cyclone forms south of the vicinity of Galveston, Tex., is found the following day south of the Appalachians near West Florida with only a slightly lower central pressure, and then deepens at an increasing rate while presumably curving northward in the Atlantic coastal region. For the autumn and spring no typical cyclone can be described because of the greater variations during these months.

PRECIPITATION ASSOCIATED WITH THE CYCLONES

In order to determine some relationship between the cyclones and the rainfall received in the land area most often affected by the cyclones, daily precipitation records from certain stations recorded in *Climatological Data for the United States by Sections* for the years 1928 through 1938 were analyzed. A 2-day interval embracing each cyclone formation was considered most suitable for all stations in the region (fig. 13). Since the daily synoptic charts were drawn for approximately 0700 local time (1300 GMT) and the rainfall period at each station was from midnight to midnight, the rainfall data cover the period beginning 7 hours before and ending 41 hours after the time assigned to each cyclone formation. All cyclones and stations were treated in this same manner, irrespective of location of formation, motion, or intensity. For this 11-year period the cyclones occurring during the months of October and April were not included in the analysis. A total of 95 storms occurred during the remaining months.

The average amount of rainfall during the 48-hour period (fig. 13) increases coastward and eastward to the Mississippi River; east of the Mississippi, where the storm tracks diverge greatly, the amount decreases more slowly. The average cyclone gives less rainfall in January and February than in the other months at Dallas, Shreveport, Vicksburg, Memphis, and Nashville; this points out the southward shift of cyclone tracks with the advance of winter and the northward shift in spring. In late winter the maximum rainfall per cyclone shifts eastward to the vicinity of Montgomery, toward the region with greatest late winter rainfall, although there is no distinct tendency for cyclones to form at a more easterly location at this time. This is probably related to the rate of deepening shown in table 1, to the predominant tracks south of Montgomery in this part of the season, and to the inevitable result of the spreading area of the cyclone with the resulting capacity for greater northward moisture transport as it moves eastward from the Texas-Louisiana coast.

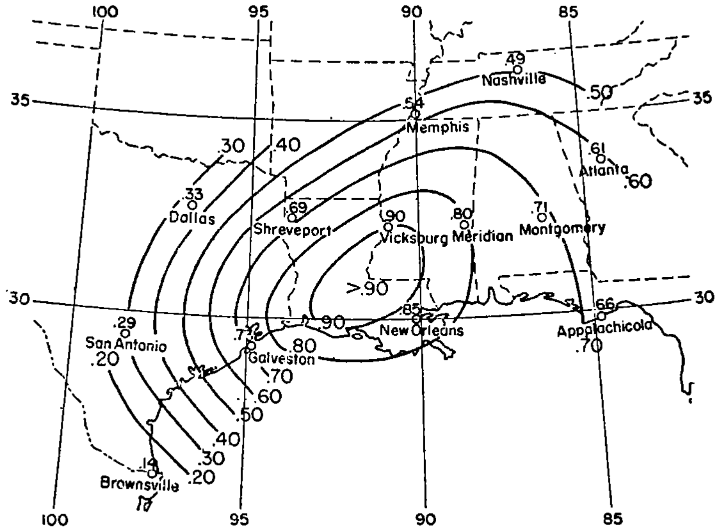

FIGURE 13.—Average 48-hour amount of rainfall (inches) associated with each cyclone during 11 seasons, November through March, 1928–1938.

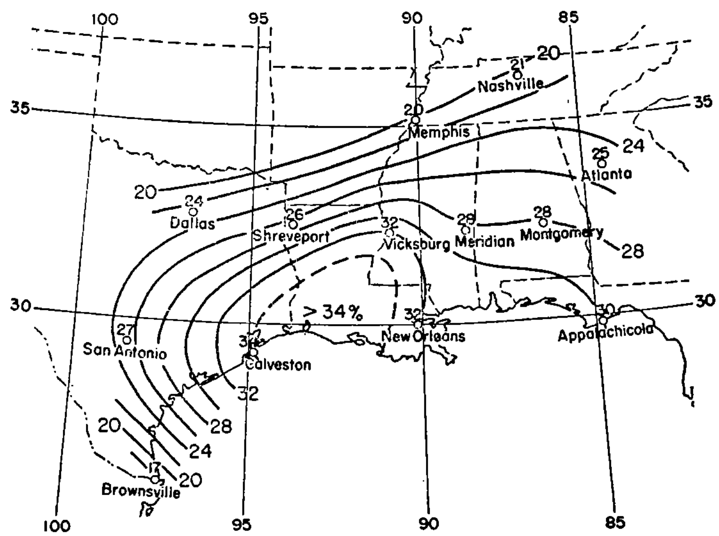

FIGURE 14.—Average percentage of the monthly rainfall attributed to the cyclones, November through March, 1928–1938.

As shown by figure 14 southern Louisiana and extreme southeastern Texas are the most dependent on these cyclones for their cold season rainfall. This reflects the great frequency and concentration of cyclogenesis immediately off the Texas coast. The seasonal distribution of the percentage of rainfall due to these cyclones shows a maximum in winter for all stations except Memphis and Nashville. At these places the effect is greater during the transitional months of spring and autumn when the storm tracks are nearer these stations.

An additional result obtained from the rainfall statistics is that the cyclones alone account for less than one-third of the total seasonal precipitation over the extreme Lower Mississippi Valley (Louisiana). This feature is verified by both the 11-year period in figure 14 and the data for the entire 40 years. Perhaps the annual average of 10 selected cyclones is small in comparison with the total number of rain-producing disturbances. It is true not only that numerous small cyclonic circulations with rain areas did not persist long enough to be included among the selected cyclones but also that much of the heavy precipitation during these months occurred with transient storms. And large amounts of rain fell in the absence of surface cyclones in the immediate vicinity. It becomes evident that the greater portion of Louisiana rainfall during these months is due to factors other than the cyclones included in this study.

As indicated by figure 10 there is a positive relation between cyclone frequency and average precipitation over the central Gulf Coast. The correlation coefficient between cyclone frequency and inches of rainfall for each season November to March during the forty years is +0.3. The regression of cyclones on rainfall for the same period shows that about 70 percent of the rainfall must be attributed to other causes, the same conclusion reached from figure 14. But regardless of this apparently minor role cyclones have on the total rainfall, there are parallel interseasonal changes in these two variables. This is readily borne out by figure 10. The contingency of cyclones and Louisiana rainfall for each season of five months in the last eleven years is shown in table 2. The two seasons having greater than average number of cyclones and less than average rainfall are borderline; each had nine cyclones and less than two inches below average rainfall.

TABLE 2.—*Tetrachoric relation between cyclone occurrence and Louisiana rainfall, 11 seasons, November through March 1928 to 1938*

Rainfall	8 or fewer cyclones	9 or more cyclones
<25.07	5	2
>25.07	0	4

Average number of cyclones per season=8.6
Average rainfall per season=25.07 in.

STATISTICS ON THE CYCLONE GROUPS

The classification of cyclones into the groups described in the early sections of this paper was applied to the 388 cases to obtain some statistical features of each group. Since for most of the 40-year period only sea level charts were available, the sequences at the surface necessarily became of primary importance; the associated upper flow patterns and sequences were only indirectly determined. Each cyclone was placed in the group which most closely resembled its synoptic pattern and type of formation.

A frequency distribution for each group is given by months in table 3. The cyclones forming with the aid of the cut-off Southwest Low have a maximum frequency during mid-winter and a rather symmetrical distribution from October to April. However, there are irregular distributions in the two situations under which the cyclones form. During late winter, when the westerlies reach their minimum latitude and the polar front is semipermanent along the Gulf Coast, the first group is more frequent and the second group reaches a seasonal low. The second group has its peak during fall and early winter, and there appears to be a slight secondary maximum in the spring. Cyclones included in the third group are preferred during the colder months, as are most of the cyclones associated with the Great Plains trough. In the fourth group are the cyclones which form after rapid northward shift of the westerlies and abrupt trough development over the western Plains; these are at a minimum in late winter. The cyclones described by the fifth group are generally winter phenomena although there is no ready explanation for the frequencies in February and March.

The favored location for the formation of the first and third groups, which occur mostly in winter, is over the coastal waters of the Gulf of Mexico. The second group appears at scattered locations within the area, similar to the locations for November in figure 11. Cyclones of the fourth group are usually more continental; they are found mostly to the north and west of the other groups. Such cyclones are believed to be frequent also in the Oklahoma-Kansas region. They are the most independent of the coastline temperature fields. The last group is found only in the eastern half of the area; its frequency would probably increase east of the Mississippi River.

Cyclones associated with the Southwest Low generally follow a course between east-northeast and east, those in the first group following this course with greater regularity. Group 3 cyclones have the most variable tracks, yet comparatively few do not move toward the northeast quadrant. The last two groups move toward the northeast quadrant almost without exception. These cyclones show the greatest tendency to move between north and northeast from their origin.

On the average the most rapidly moving storms are Groups 5 and 4, respectively, and the most sluggish are Group 2. In probability of deepening the order is similar to the order of speed, that is, Groups 4 and 5 show the greatest one-day deepening while Group 2 shows the least. Although Group 4 cyclones usually have the most ill-defined frontal structure at the surface in their early stages and move very rapidly, they are the most susceptible to deepening.

TABLE 3.—*Distribution of cyclone groups by months, 1899 to 1938*

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Totals
Southwest Low	16	23	25	38	30	26	11	169
1. Low Latitude Westerlies	1	5	13	25	27	17	4	92
2. High Latitude Westerlies	15	18	12	13	3	9	7	77
Great Plains Trough	15	23	49	45	41	30	16	219
3. Retrograde and Miscellaneous	11	16	33	31	37	17	7	152
4. Discontinuous Redevelopment	4	4	13	10	2	5	9	47
5. Persistent Trough	0	3	3	4	2	8	0	20

SUMMARY

The great frequency with which surface cyclones emanate from the Texas-West Gulf coastal region can be accounted for by the unique physiography of the environment. In addition to control by the general circulation, frontogenesis and cyclogenesis in this region are favored by the influences of the warm-water surface of the Gulf of Mexico providing both a temperature contrast and moisture source, the cold continental air mass source region to the north, and the mountain barrier to the west. The frequency with which the polar front is in the vicinity of the north Gulf coast and the natural land-water temperature contrast in winter make the coast a semipermanent low-level frontal zone; in summer and in the region to the west this effect is almost negligible. The effect of the mountains on Texas cyclogenesis is both direct and indirect. A large number of these cyclones compensate for the relative absence of surface cyclogenesis between the Pacific Ocean and the Gulf of Mexico at the same latitudes; the upper level perturbations are carried eastward to the more favorable influences of the Gulf coastal region for surface cyclonic development. Also, the mountains aid dynamically in maintaining anticyclonic (or less cyclonic) curvature of air flow in the middle troposphere over western North America and cyclonic curvature east of the mountains. This effect is shown in the mean circulation and has been described by Fultz [11], by Namias and Clapp [12], and more recently by Boffi [13]. As a result of the increased southward component of motion over the Great Plains, cold air is steered farther southward and with greater frequency to the Gulf coast. As a western barrier to very cold masses of air spreading from Canada, the Rocky Mountain Range serves a similar effect in providing for northwest currents at upper levels. The surface lee-of-the-mountains warm trough in its basic sense is not considered to be an important forerunner in Texas cyclone formation.

From the description of several sequences and patterns in Texas cyclone formation it is possible to deduce the general synoptic principle involved. The four groups most typical of this region all involve a discontinuous westward shift in the location of maximum upper level cyclonic activity over North America; the other group (Group 5) can be viewed along the same lines since it consists of a marked retardation in the eastward progression of the primary trough with small short-period oscillations in trough position. Therefore, the cyclones are not associated with the primary southward push of cold air; they usually are found south and west of the preceding cold dome of the eastern states. The cyclones seldom occur immediately after a deep cold air mass has penetrated the southern extents of the Gulf of Mexico; they are most common when the bulk of the cold air at low levels is retained north of the Gulf coast.

The basic wave pattern of the westerlies from which the cyclones are to be anticipated consists of trough over eastern North America, ridge near the west coast, and trough over or just east of the central Pacific. Again, the last group of cyclones is different; its wave pattern has been described sufficiently. Very little definite information can be given on latitude, strength, and amplitude of the westerlies during cyclone formation because they vary not only with type of formation but also with individual cases.

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